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13. ABSTRACT
Results are presented of a preliminary study to determine the possibility of using limited or partial similitudes to determine the general level of damage that results from high-speed particle impact. Experimental results are presented and compared for four separate types of impact which satisfy a certain partial similitude. The similarity of impact damage for these conditions is discussed for both simple and compound targets.

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A BRIEF STUDY OF THE POSSIBILITY OF USING PARTIAL SIMILITUDES TO ESTIMATE THE LEVEL OF IMPACT DAMAGE

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and
Brian H. Jones

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I. INTRODUCTION

In the past twenty years, great strides have been made in developing computer codes which permit one to calculate the details of certain relatively simple hypervelocity impacts. Such computations are relatively expensive and, as the complexity of the impact increases (let us use grazing impact upon a complex finite target as an example), the accuracy of the results that are obtained decreases. In these cases, one is forced to rely on experimental measurements to determine the details of a given impact. These experimental measurements are also expensive to obtain and, in many cases, one desires information about a great many types of closely related impacts, so the question arises as to whether or not one can use certain similitude arguments to relate one set of impact measurements to another.

Let us consider a specific example. Suppose one is in possession of the results of several shots of a glass pellet 1/4 inch in diameter at 6,000 ft/sec into a large, flat aluminum target 1/2-inch thick. Suppose the angle of impact is 30 degrees. We may ask ourselves the question, what other combinations of pellet, target material, and impact velocity will give an equivalent (or nearly equivalent) crater? This is a matter of similitude. There is not much question that one could scale this impact to the impact of a 1/2-inch diameter similar glass ball into a large, 1-inch thick similar aluminum plate at 30 degrees and 6,000 ft/sec. In this case, since every important nondimensional parameter governing the phenomena is identical in the two cases, the impacts should be similar, with each important detail of the crater scaling as the diameter of the pellet.

The similitude just described is too simple to be useful, but one may ask whether another impact between different materials at a different velocity will produce a crater of the same class as far as the general level of damage is concerned although the details of the crater may be somewhat different.

In this report we attempt to establish the feasibility of developing a rationale for the use of similitude in impact evaluation. Although the idea is now new (Morrison[1] has studied the similitude of meteoroid impact by the use of dense projectiles), it is clear that not enough study has been made of the possibility of using similitudes in the classification of impact damage. This is particularly true when one considers the possible savings in expenditure for data points that might result from a developed understanding of impact similitude.

[1]Morrison, Robert H.: Simulation of Meteoroid-Velocity Impact by Use of Dense Projectiles, NASA TN D-5734, April 1970.

II. IMPACT SIMILITUDE

A similitude exists in any two physical situations if all the nondimensional parameters that can be formed from the physical magnitudes in any two situations are equal. As an example: if, for the flow of a simple perfect gas, the Reynolds number $\rho Vd/\mu$ and the Mach number V/a are equal in two situations, the two flows will be similar about similar objects. That is to say, the nondimensional forces and moments C_L, C_D, C_M, etc., will be equal at equal angles of attack.

For the case of two impacts, it is virtually impossible to achieve a true similitude except a scaling similitude such as that mentioned in the introduction. The reason is that there are so many nondimensional parameters that enter into any hypervelocity impact that one cannot, in general, find two matching impacts if the materials involved are not identical. As an example, let us consider some of the nondimensional parameters which must be equal in two impacts if the results of impact are to be similar. Consider a target consisting of an infinite flat plate of thickness d_t being struck at an angle θ by a spherical pellet of diameter d_p. First of all, we require geometrical similarity of the two impacts; i.e.,

$$\theta_1 = \theta_2$$

and

$$(d_t/d_p)_1 = (d_t/d_p)_2$$

Next we require equivalent energies in the two cases

$$\left(E_{1_t}/E_p\right)_1 = \left(E_{1_t}/E_p\right)_2$$

and

$$\left(E_{1_p}/E_p\right)_1 = \left(E_{1_p}/E_p\right)_2$$

In these expressions, E_{1t} and E_{1p} are the energies for target and pellet, respectively, that are required in the i^{th} mode of energy absorption for a volume of each material equal to the volume of the pellet. Some of the various modes of energy absorption might be:

a. The energy required to bring the pellet or an equivalent volume of target to its melting temperature;

b. The energy required to fuse each material at its melting temperature;

c. The energy required to take the fused material of target and pellet to the vaporization temperature of each.

There are many more, such as the energies required to reach significant points on the stress strain curves of each material, etc., etc. It does not seem pertinent to list all the significant energies in this short report. Suffice it to say that if we consider two target materials they must have completely similar nondimensional equations of state if we are to be able to exhibit a complete similitude. In the above expressions, E_p is, of course, the energy of the pellet $m_p V^2/2$.

To continue our list of other pertinent nondimensional parameters, we will also require for similarity that the density ratios of the two materials be the same; i.e.,

$$(\rho_t/\rho_p)_1 = (\rho_t/\rho_p)_2$$

We also require similarity of Mach numbers:

$$(V/a_t)_1 = (V/a_t)_2$$

and

$$(V/a_p)_1 = (V/a_p)_2$$

The nondimensional parameters listed above are but a sampling of all the quantities which must be matched if we are to have complete similarity of impacts. It should be obvious that complete similarity, except a scaling similarity between impacts of identical materials, is a most improbable affair.

At this point it is necessary that we back off from the notion of complete similarity and inquire as to whether one can achieve a partial, although not complete, similitude if only a few nondimensional parameters are held fixed between two impacts.

As implied by the use of the words "partial similitude," what we are striving for is the establishment of some scheme by which we can identify impacts which are of the same class insofar as the degree of damage sustained by a target is concerned. In other words, we do not expect the details of the damage to be similar, but we hope to achieve similarity insofar as the level of damage is concerned.

The question that was addressed in designing the impact tests reported in the remainder of this paper was the plausibility of the notion of partial impact similitude for establishing the general levels of damage during impact.

III. CHOICE OF PARAMETERS FOR PARTIAL SIMILITUDE

The number of nondimensional parameters that are important in a given impact is very large and there does not seem to be any purely rational way of ordering the importance of the various ratios insofar as damage level is concerned for a completely general impact. Our approach, for this investigation, has been to consider pellets of length-to-diameter ratio of the order of unity and to select several parameters which are intuitively appealing and attempt to establish by experiment whether rules for partial similitude can be successfully constructed from these parameters.

The parameters that were chosen were the following:

$$\frac{E_{m_p}}{E_p} = \frac{\text{Energy to melt the pellet}}{\text{Energy of the pellet}}$$

$$\frac{E_{m_t}}{E_p} = \frac{\text{Energy to melt a pellet volume of the target}}{\text{Energy of the pellet}}$$

$$\frac{p_i}{\sigma_p} = \frac{\text{Initial impact pressure}}{\text{Strength of the pellet}}$$

$$\frac{p_i}{\sigma_t} = \frac{\text{Initial impact pressure}}{\text{Strength of the target}}$$

In addition to the requirements that

$$\left(E_{m_t}/E_p\right)_1 = \left(E_{m_t}/E_p\right)_2 \tag{1}$$

$$(p_i/\sigma_t)_1 = (p_i/\sigma_t)_2 \tag{2}$$

$$\left(E_{m_p}/E_p\right)_1 = \left(E_{m_p}/E_p\right)_2 \tag{3}$$

$$(p_1/\sigma_p)_1 = (p_1/\sigma_p)_2 \tag{4}$$

we require geometric similitude of the two impacts.

If geometric similitude is achieved and all conditions (1) through (4) are achieved, we, in the remainder of this report, refer to this situation as a partial similitude of Class I. In this case, the nondimensional parameters based on energy and pressure are satisfied for both target and pellet.

If only geometric similitude and conditions (1) and (2) are met, so that there is partial similitude with respect to the target only, we will refer to this condition as a partial similitude of Class II.

As will be seen in what follows, it appears that in many cases similitudes of Class II may be usefully employed to estimate target damage levels and, since they are much more easily achieved experimentally than similitudes of Class I, this first preliminary study to determine the plausibility of partial similitude was carried out for a set of Class II similitudes.

IV. TESTS FOR PARTIAL SIMILITUDE

In order to test the notion of partial similitude, a set of five cylindrical targets measuring 7 inches o.d., 1/2-inch thick, and 9 inches long were made. Three of these targets were made of 6061T6 aluminum and two of 101/66 nylon. (The reasons for choosing these materials (and those used for projectiles) are outlined in the appendix.) As a basic reference event, we chose the impact of a 1/4-inch diameter nylon sphere at a nominal velocity of 20,000 ft/sec into an aluminum target. Two such shots were made in the NRL light gas gun facility in order to establish the reference impact.* These two reference impacts are shown in Figures 1 through 4. Figures 1 and 2 are front and back views of a reference impact obtained at 19,480 ft/sec, and Figures 3 and 4 are front and back views of a reference impact at 20,077 ft/sec. The four nominal nondimensional parameters for this impact were

$$\frac{E_{m_t}}{E_p} = 0.204 \tag{1}$$

$$\frac{p_1}{\sigma_t} = 147 \tag{2}$$

$$\frac{E_{m_p}}{E_p} = 0.0327 \tag{3}$$

$$\frac{p_1}{\sigma_p} = 605 \tag{4}$$

A search for a material which would match conditions (1) and (2) and hence achieve a partial similarity of Class II yielded several possibilities of which the following three examples were chosen:

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*The authors would like to extend their thanks to Mr. Mario Persechino of the Hypervelocity Techniques Branch of NRL for his cooperation and support and carrying out the experimental portion of this study.

Similarity #1. A 1/4-inch diameter aluminum pellet into an identical 6061T6 cylinder at 13,250 ft/sec

Similarity #2. A 1/4-inch diameter polyethylene pellet into a nylon cylinder at 9,350 ft/sec

Similarity #3. A 1/4-inch diameter aluminum pellet into a nylon cylinder at 5,450 ft/sec

Although the nominal velocities required for partial similitude were not attained exactly, Figures 5 through 10 show the results of a single shot test aimed at achieving the three similarities listed above.

Figures 5 and 6 show front and back views of attempted similarity #1. Actual conditions were 12,401 ft/sec. It will be noted that, although the general spread of the damage in the target was similar to the reference impact, complete penetration was achieved in this case whereas only incipient penetration was achieved in the reference event. This, in all probability, has a lot to do with the fact that the similitude is of Class II and the aluminum pellet does not break up as easily as does the nylon pellet of the reference shot at the energy level of the impact.

Figures 7 and 8 show the front and rear views of attempted similarity #2. The actual impact velocity was 8,780 ft/sec. In this case, it is clear that, although the details of the target damage are somewhat different, the general levels of both front and rear spall damage are quite similar. In this case it is worth noting that the pellet is again breaking up more readily as in the reference impact.

Figures 9 and 10 show the front and back views of attempted similarity #3 for which actual conditions were 5,605 ft/sec. Again, the general levels of target damage are similar. Here again, because conditions on the pellet did not favor pellet breakup, puncture was complete and, in fact, the whole event is more equivalent to similarity #1 than to the reference impact, as might be expected.

A summary of these first similarity tests is given in Table 1 where, in addition to the basic physical condition of the target and the pellet, the experimentally achieved values of the four nondimensional similarity parameters are given.

A review of Figures 1 through 10 and a comparison of the similarity parameters for these tests given in Table 1 would lead one to believe that there may be some merit and utility to the idea of partial similitude. Certainly the levels of damage sustained by the targets are quite similar, and the departures from truly close similarity seem to be connected to the lack of equivalence in regard to the pellet similarity parameters.

Table 1

Round No.	Target				Projectile			
	O.D. Cylinder (inches)	Length Cylinder (inches)	Thickness Cylinder (inches)	Material	Diameter (inches)	Material	Velocity (ft/sec)	Impact Angle (deg)
1-1-757	7	9	0.500	Aℓ6061T6	0.25	Nylon	19,480	90
1-1-758	7	9	0.500	Aℓ6061T6	0.25	Nylon	20,077	90
0-481	7	9	0.500	Aℓ6061T6	0.25	Aluminum	12,401	90
5-791	7	9	0.500	Nylon	0.25	Polyethylene	8,780	90
0-476	7	9	0.500	Nylon	0.25	Aluminum	5,605	90

Round No.	Similarity Parameters			
	E_{m_t}/E_p	p_1/σ_t *	E_{m_p}/E_p	p_1/σ_p
1-1-757	0.217	134	0.0346	552
1-1-758	0.204	147	0.0327	605
0-481	0.234	132	0.233	132
5-791	0.211	96	0.0567	436
0-476	0.183	98	1.145	22

*The differences in p_1/σ_t in these tests (and those defined in Table 2) are due to the strengths of the target materials differing slightly from those assumed in the similitude calculations.

V. FURTHER TEST OF SIMILARITY

In addition to the similarity tests on simple targets just presented, several tests of similarity in more complex targets were carried out in this initial evaluation of the concept. The more complex targets consisted of compound targets nominally 7 inches in outside diameter, 9 inches long, and 1/2-inch thick. The thickness was made up of a nominal 4/10 inch of aluminum or nylon backed by 1/10 inch of steel in the case of an aluminum outer cylinder and commercially pure magnesium in the case of a nylon outer cylinder. The exact dimensions of the targets for this series of tests are given in Table 2.

In this series of tests, the nominal reference event was taken to be the impact of a 1/4-inch nylon sphere at 20,000 ft/sec upon the steel-lined aluminum cylinder. In selecting the Class II similitudes that might be related to this reference event, two further equivalence ratios were required of the targets for similarity. These additional requirements for similarity were that the ratio of strengths of the outer and inner cylinders was to be the same and the ratio of acoustic impedances in the two materials was to be the same; i.e.,

$$\left(\frac{\sigma_{t\ \text{inner}}}{\sigma_{t\ \text{outer}}}\right)_1 = \left(\frac{\sigma_{t\ \text{inner}}}{\sigma_{t\ \text{outer}}}\right)_2 \tag{5}$$

and

$$\left[\frac{(\rho_t a_t)_{\text{inner}}}{(\rho_t a_t)_{\text{outer}}}\right]_1 = \left[\frac{(\rho_t a_t)_{\text{inner}}}{(\rho_t a_t)_{\text{outer}}}\right]_2 \tag{6}$$

These two conditions were met approximately by the selection of magnesium to back nylon as roughly equivalent to the reference target of steel backing aluminum, as can be seen from the following numbers:

Table 2

Round No.	Target				Projectile			
	O.D. Cylinder (inches)	Length Cylinder (inches)	Thickness Cylinder (inches)	Material	Diameter (inches)	Material	Velocity (ft/sec)	Impact Angle (deg)
1-1-759	7	9	0.400 0.115	Aℓ6061T6 Steel 4130	0.25	Nylon	19,973	90
1-1-761	7	9	0.399 0.101	Aℓ6061T6 Steel 4130	0.25	Nylon	19,616	90
0-480	7	9	0.400 0.091	Aℓ6061T6 Steel 4130	0.25	Aluminum	12,861	90
0-482	7	9	0.400 0.100	Aℓ6061T6 Steel 4130	0.25	Aluminum	13,707	90
5-795	7	9	0.400 0.100	Nylon Magnesium	0.25	Polyethylene	7,400	90
0-477	7	9	0.405 0.100	Nylon Magnesium	0.25	Aluminum	5,391	90

Round No.	Similarity Parameters			
	E_{m_t}/E_p	p_i/σ_t	E_{η_p}/E_p	p_i/σ_p
1-1-759	0.206	138	0.0330	575
1-1-761	0.214	135	0.0341	565
0-480	0.227	138	0.227	139
0-482	0.192	156	0.192	156
5-795	0.306	74	0.0817	363
0-477	0.190	92	1.195	20

$$\frac{\sigma_{t_{steel}}}{\sigma_{t_{a\ell}}} = 2.79 \qquad \frac{\sigma_{t_{mg}}}{\sigma_{t_{nylon}}} = 2.76$$

and

$$\frac{(\rho_t a_t)_{steel}}{(\rho_t a_t)_{a\ell}} = 2.92 \qquad \frac{(\rho_t a_t)_{mg}}{(\rho_t a_t)_{nylon}} = 4.57$$

Figures 11 and 12, as well as Figures 13 and 14, show front and back views of the impact damage for the reference impact. Note the slight variation in damage in these two cases which were close to identical from an impact velocity standpoint. This is typical of the scatter in tests like this of composite targets.

For comparison with the reference impact in a composite target, we select the same similarities as before.

Similarity #1. A 1/4-inch diameter aluminum pellet at 13,250 ft/sec into a cylinder consisting of 0.400 inches of aluminum 6061T6 over 0.100 inches of steel 4130.

Similarity #2. A 1/4-inch diameter polyethylene pellet at 9,350 ft/sec into a cylinder consisting of 0.400 inches of nylon over 0.100 inches of commercially pure magnesium.

Similarity #3. A 1/4-inch diameter aluminum pellet at 5,450 ft/sec into a cylinder consisting of 0.400 inches of nylon over 0.100 inches of commercially pure magnesium.

As before, although the exact velocity conditions for Class II similarity were not met in the experimental shots, Figures 15 through 21 show the results of attempts to check the three similarities listed above for the case of compound targets.

Figures 15 and 16, as well as Figures 17 and 18, show the results of an attempt to achieve similarity #1. The velocity for Figures 15 and 16 was 12,861 ft/sec; for Figures 17 and 18 it was 13,707 ft/sec. It will be noted that both the front and rear face damage levels in these two targets are very similar to the damage level sustained in the reference impact.

Figures 19 and 20 show front and back views of an attempt to achieve similarity #2. In this case, the velocity was 7,400 ft/sec. This velocity is quite low compared to the desired value of 9,350 ft/sec so that not too much can be said about similarity in this case. The general level of frontal damage was, however, somewhat lower than in the reference cases. The rear damage level was of the same order of magnitude but the type of damage, because of the different natures of steel and magnesium, was quite different. In the case of steel, there is rather a large bulge. In the case of magnesium, the bulge is of roughly the same diameter but the material is broken inward in a petalled fashion.

Figures 21 and 22 show front and back views of an attempt to achieve similarity #3. In this case the actual velocity achieved was 5,391 ft/sec. It will be noted that the general level of front and back surface damage is closely related to that of the previous round, although there appears to be slightly more surface damage on this last shot. The damage level is again the same order as that found in the reference shot with the detail of the exact behavior of the bulge being different. Two further results of this test should be pointed out. First, although the local front surface damage level in the vicinity of the crater was the same in this test as in the others, there was, in addition to the local damage, a large crack down the nylon cylinder. The exact cause of this is not known and it would be desirable to repeat this test to verify this result. Second, in this particular case, the aluminum pellet was recovered in a flattened condition, as shown in Figure 21. In the impact process this pellet had lost 0.009 grams of its original weight of 0.376 grams. As pointed out in the previous section, this result is, in all probability, because the energy level of the impact compared to the energy level that can be sustained by the pellet is very much lower in this case than in the other three examples of a Class II similitude in a compound target.

In Table 2 we list, in addition to the physical conditions for each of the impacts just described, the four nondimensional parameters that were actually achieved in these shots.

VI. DISCUSSION AND RECOMMENDATIONS

In this very brief study of the plausibility of setting up a scheme for estimating or correlating impact damage by means of partial similitudes, we have presented the results of a series of experiments designed to test the idea. The results are encouraging and indicate that it would be desirable to continue with such studies. Further studies should address two questions. First, how wide a range of materials, velocities, and geometries can be successfully attacked by this method? Second, can one make a better selection of basic similarity parameters than those initially selected for these tests?*

If, indeed, the idea of partial similitude can be shown to be useful in evaluating impact damage, the monetary savings that might be achieved by use of the method are large. In addition, it opens the way for simulation of certain impact results that cannot be achieved at the present time. As an example, consider the simulation of advanced interceptor impact and spall damage phenomena on actual components (10,000 to 15,000 ft/sec impacts) that might be carried out on existing rocket sleds (6,000 ft/sec) using dense pellets. To be sure, for this type of test, one would wish to achieve a similitude of Class I so that both target damage and pellet breakup were similar. It is our belief that such a similitude can be achieved by manufacture of dense pellets that are easily destroyed. This can be achieved by making a pellet out of a properly ground-up or powdered dense material which is held together by a suitably brittle and easily destroyed binder.

In any event, the encouraging results obtained in these preliminary tests and the advantages that might be gained if the method of partial similitude is developed into an effective art are such as to make strong support for the study and development of similarity techniques in the months ahead highly desirable.

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*This might be particularly true if one were to consider targets consisting of fiber-reinforced materials.

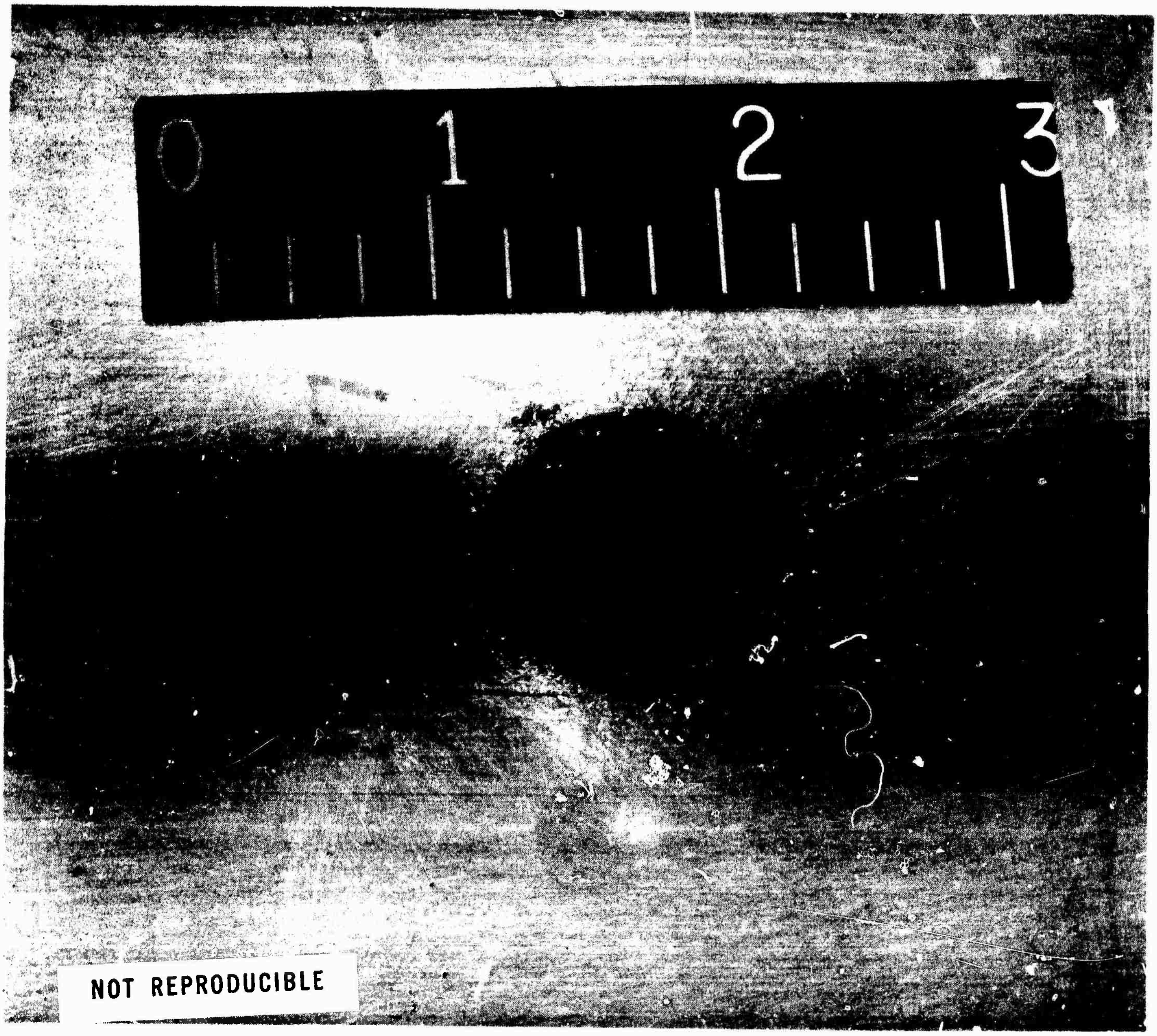

Figure 1. Nylon projectile, aluminum target (Round 1-1-757)
Front face damage (impact velocity = 19,480 ft/sec)

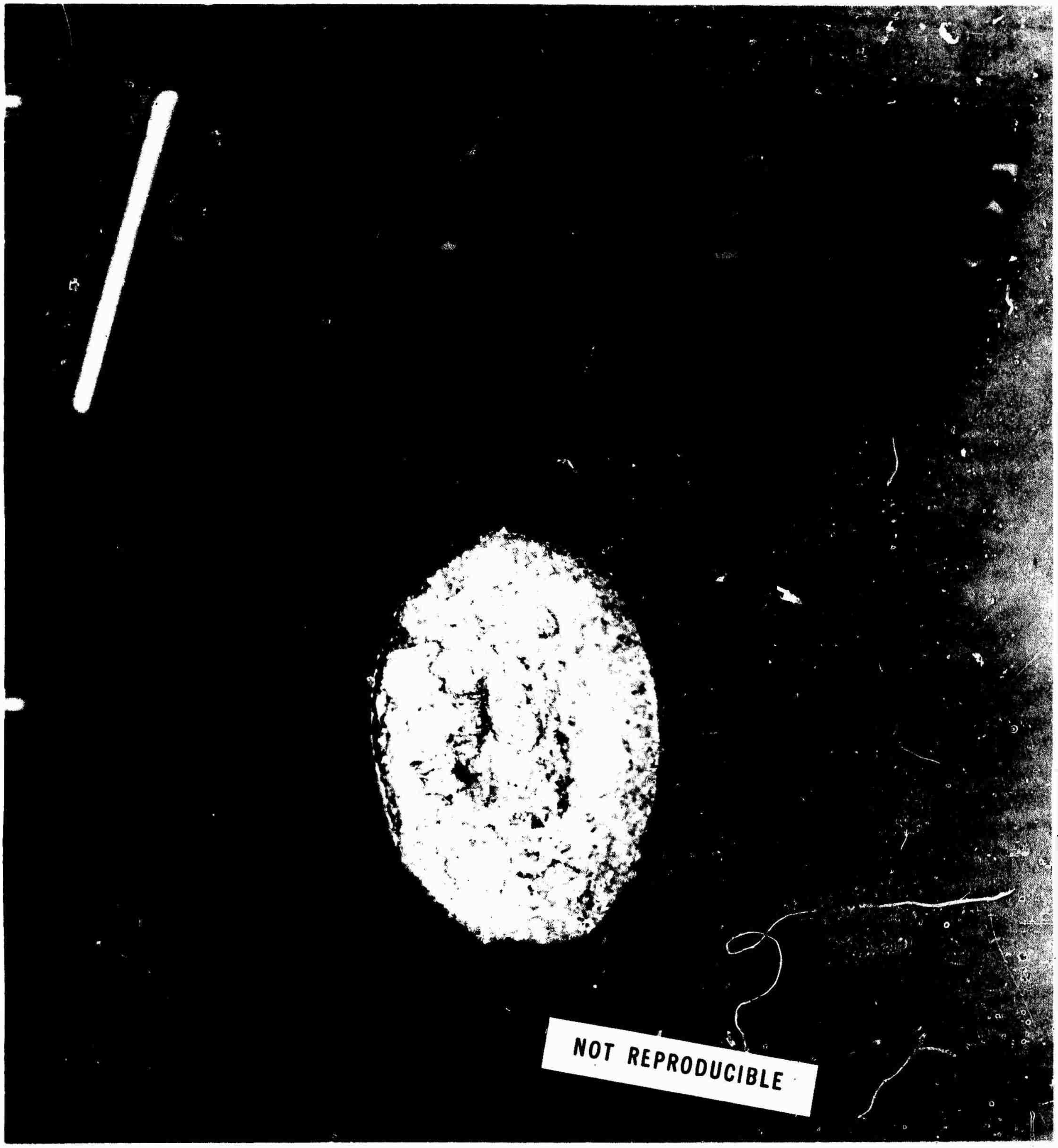

Figure 2. Nylon projectile, aluminum target. (Round 1-1-757)
Rear face damage (impact velocity = 19,480 ft/sec)

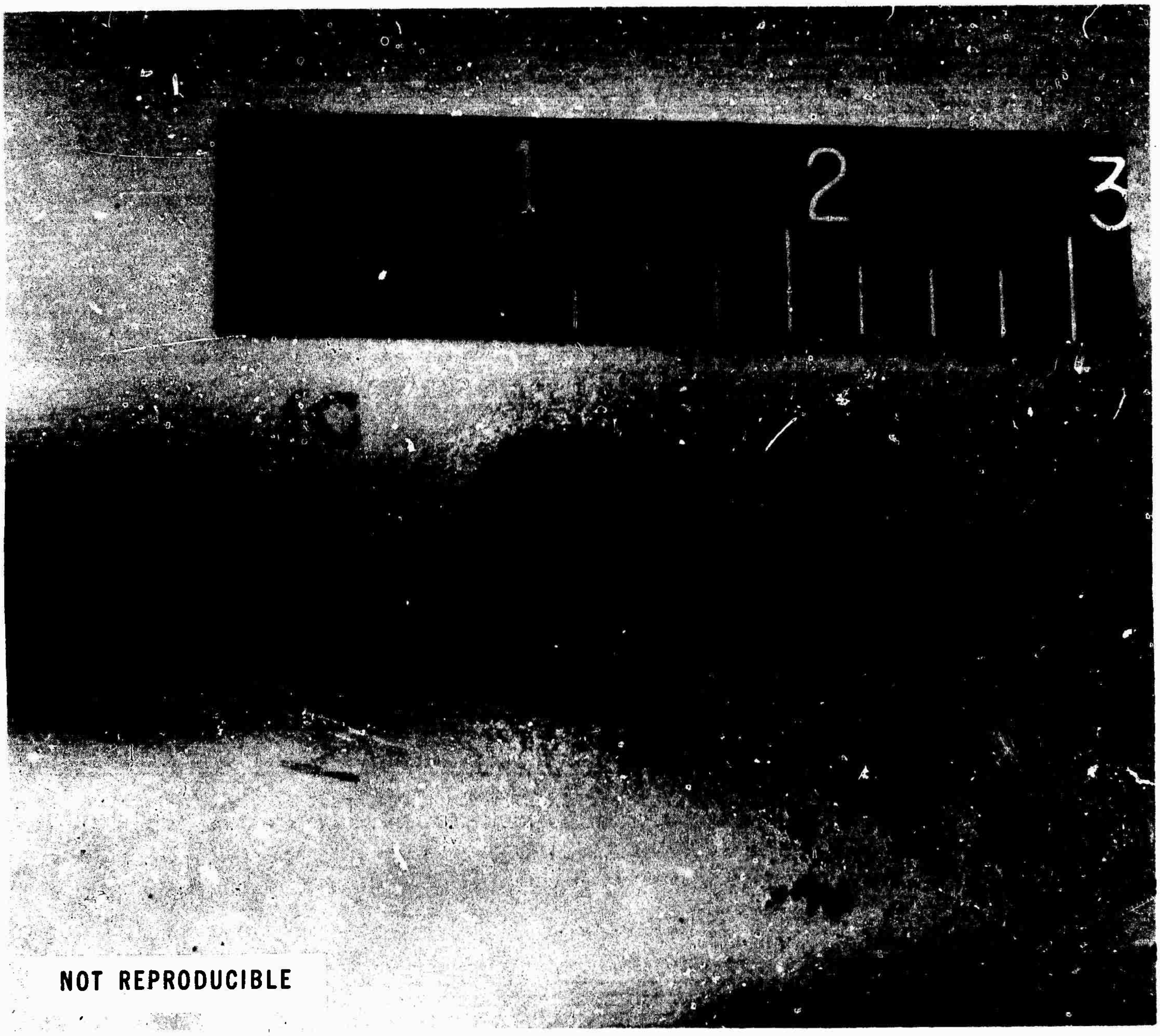

Figure 3. Nylon projectile, aluminum target (Round 1-1-758)
Front face damage (impact velocity = 20,077 ft/sec)

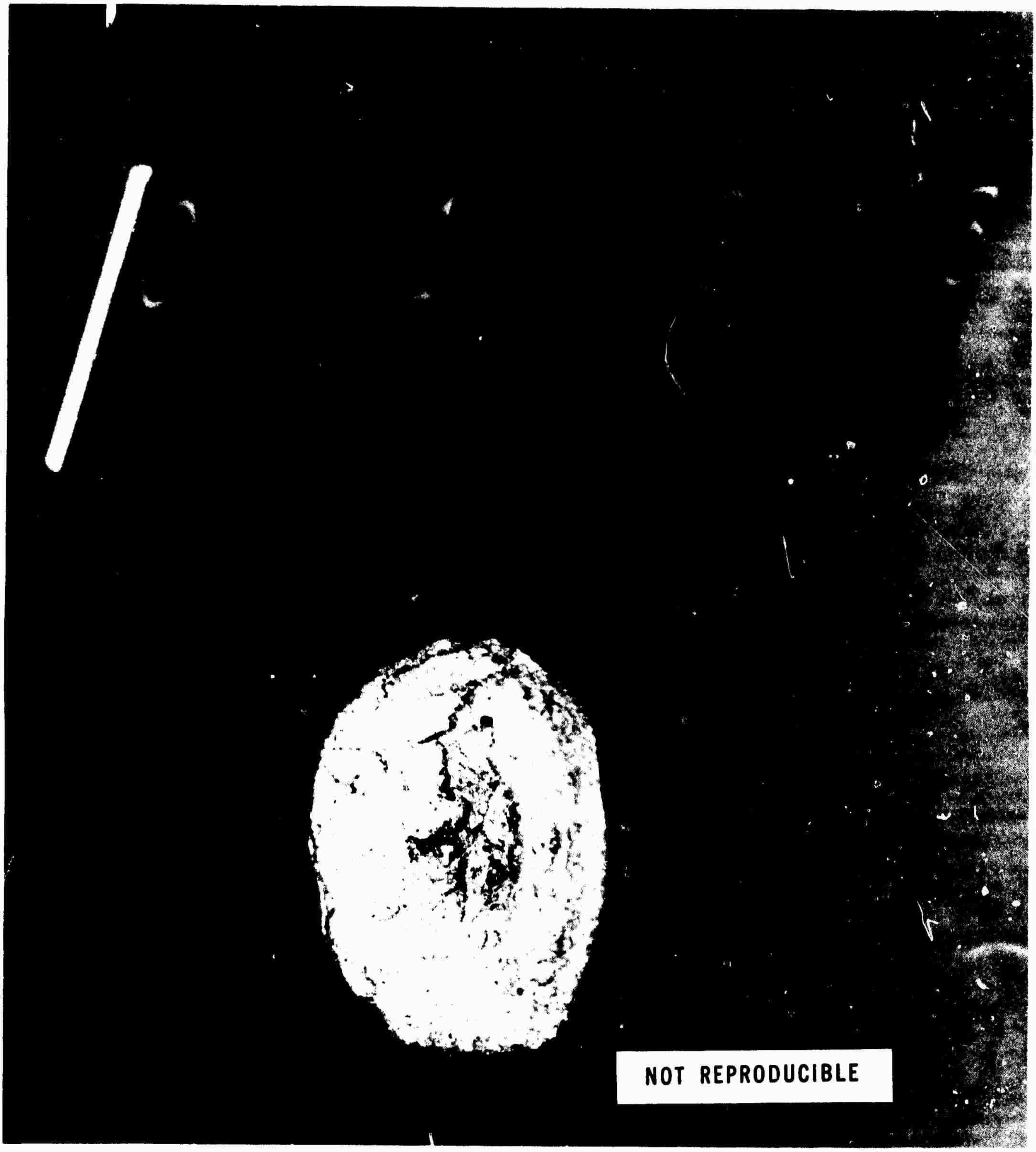

Figure 4. Nylon projectile, aluminum target (Round 1-1-758)
Rear face damage (impact velocity = 20,077 ft/sec)

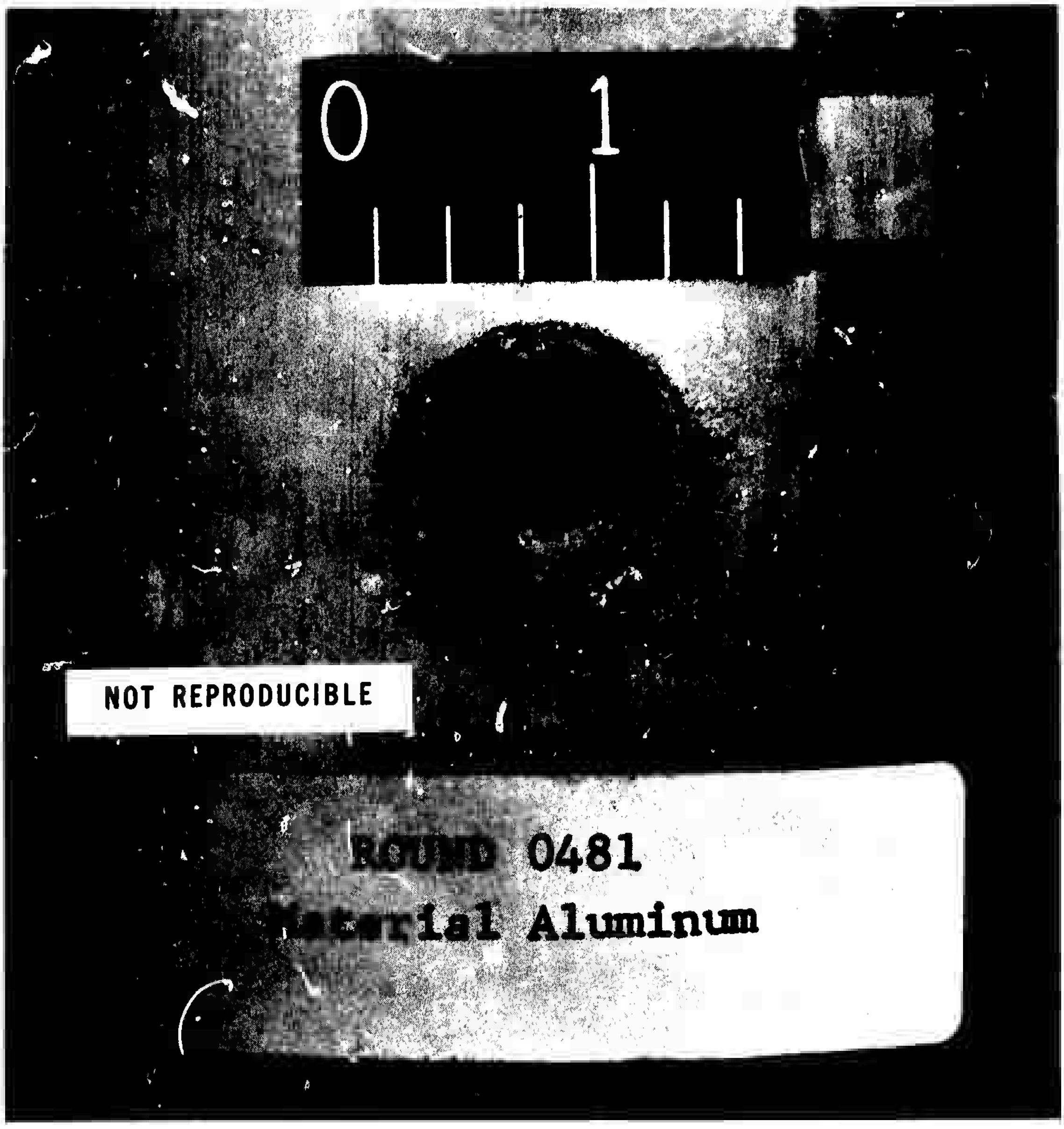

Figure 5. Aluminum projectile, aluminum target (Round 0481)
Front face damage (impact velocity = 12,401 ft/sec)

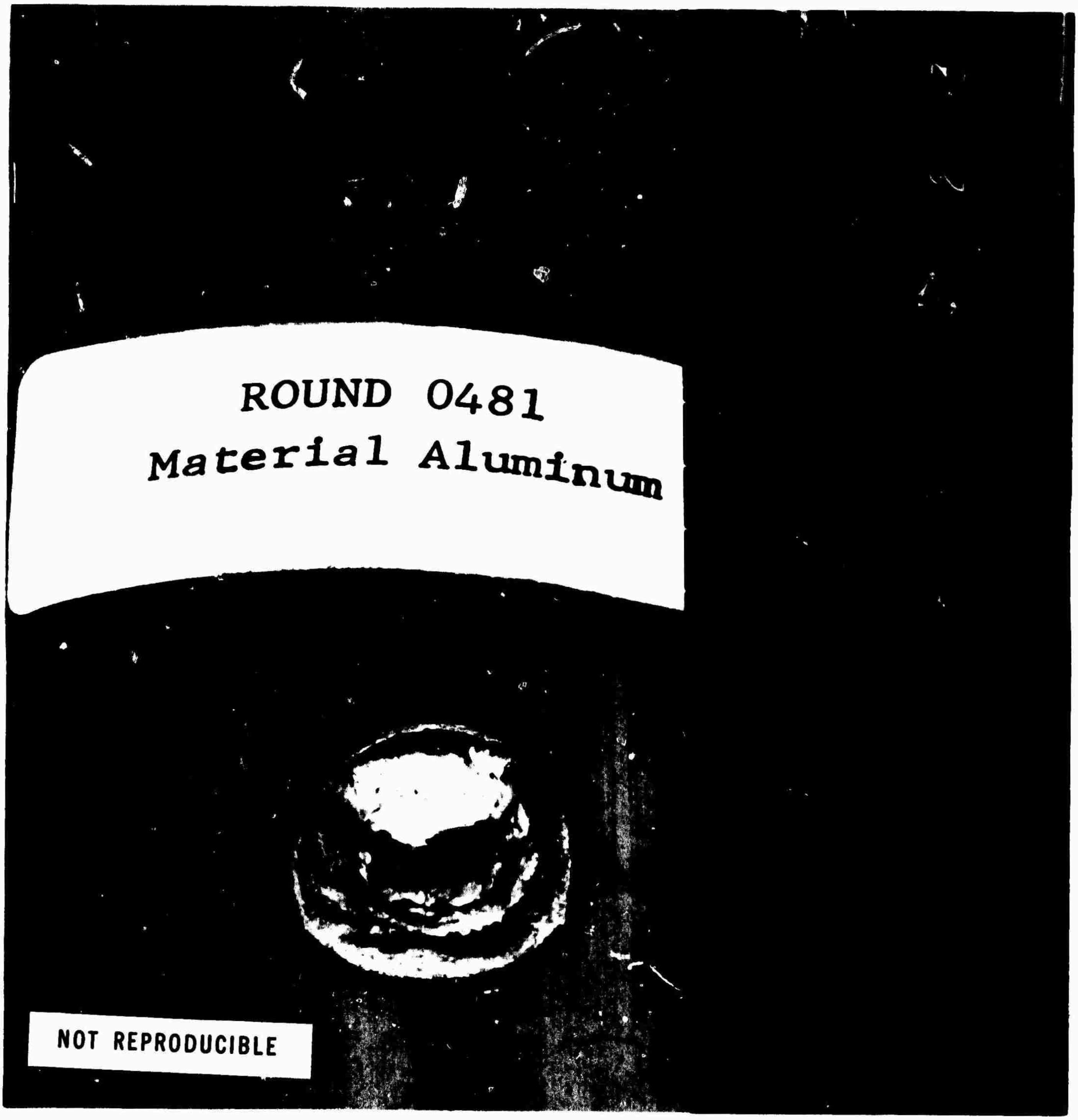

Figure 6. Aluminum projectile, aluminum target (Round 0481)
Rear face damage (impact velocity = 12,401 ft/sec)

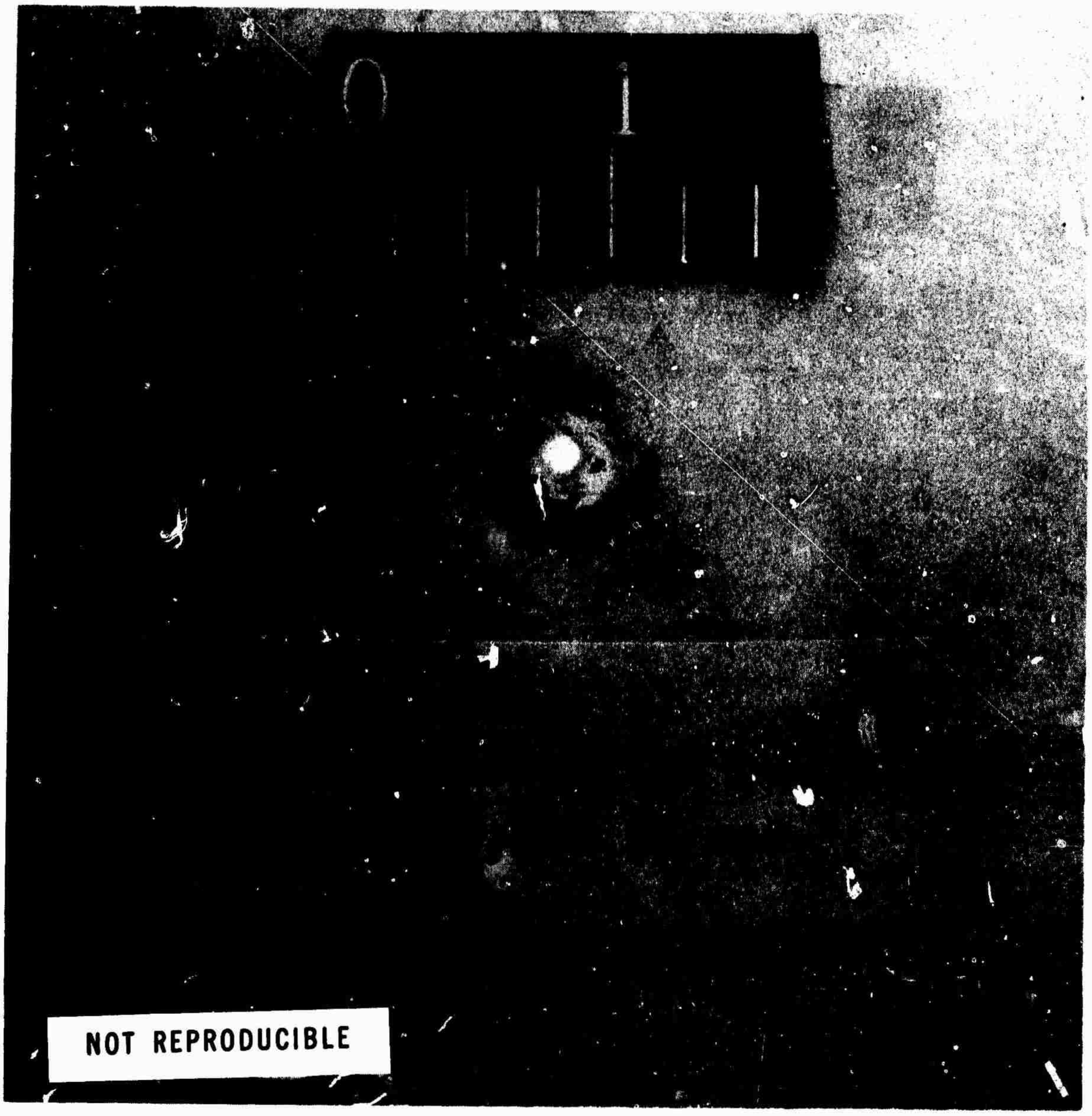

Figure 7. Polyethylene projectile, nylon target (Round 5-791)
Front face damage (impact velocity = 8,780 ft/sec)

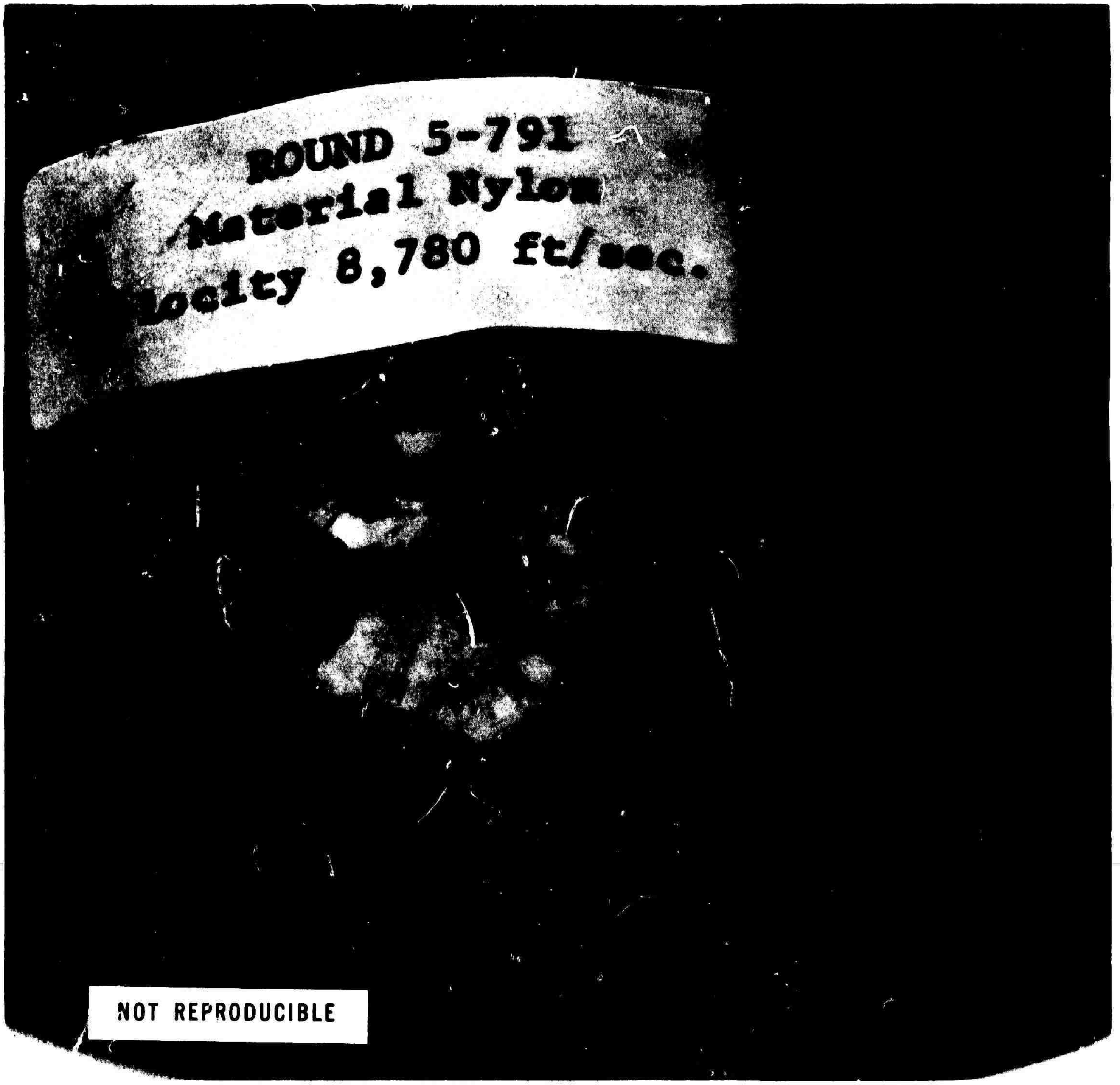

Figure 8. Polyethylene projectile, nylon target (Round 5-791)
Rear face damage (impact velocity = 8,780 ft/sec)

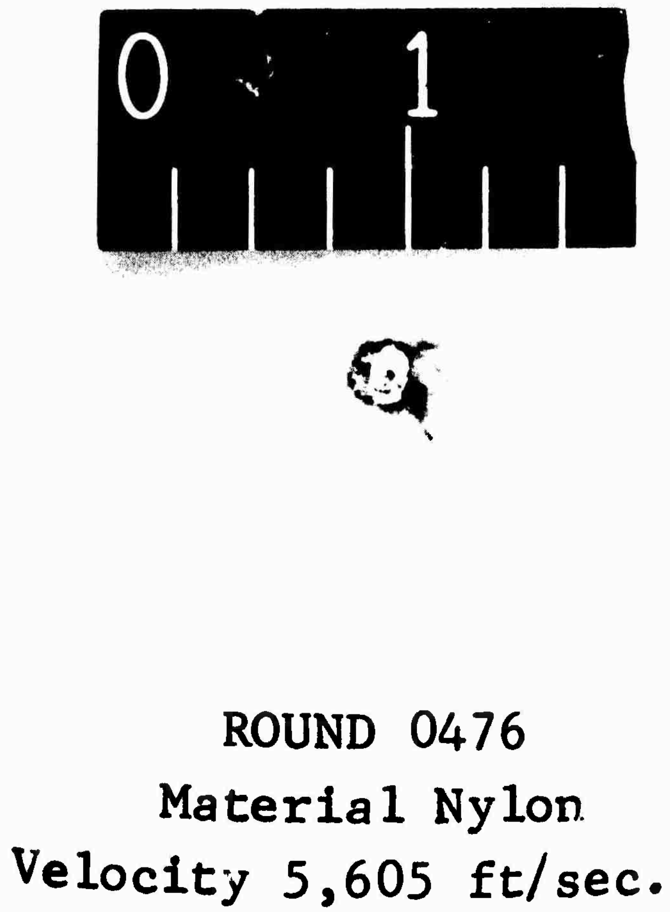

Figure 9. Aluminum projectile, nylon target (Round 0476)
Front face damage (impact velocity = 5,605 ft/sec)

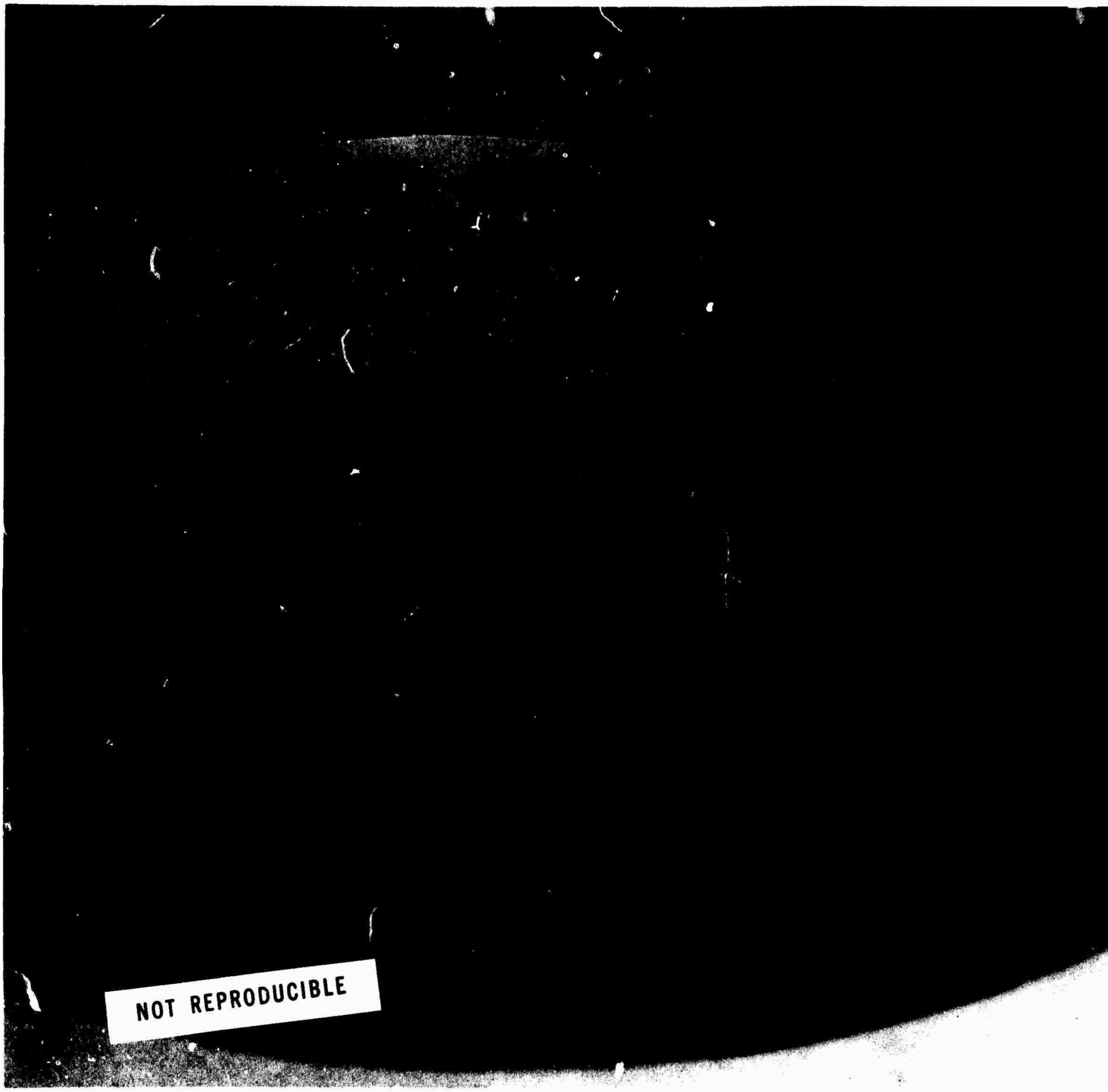

Figure 10. Aluminum projectile, nylon target (Round 0476)
Rear face damage (impact velocity = 5,605 ft/sec)

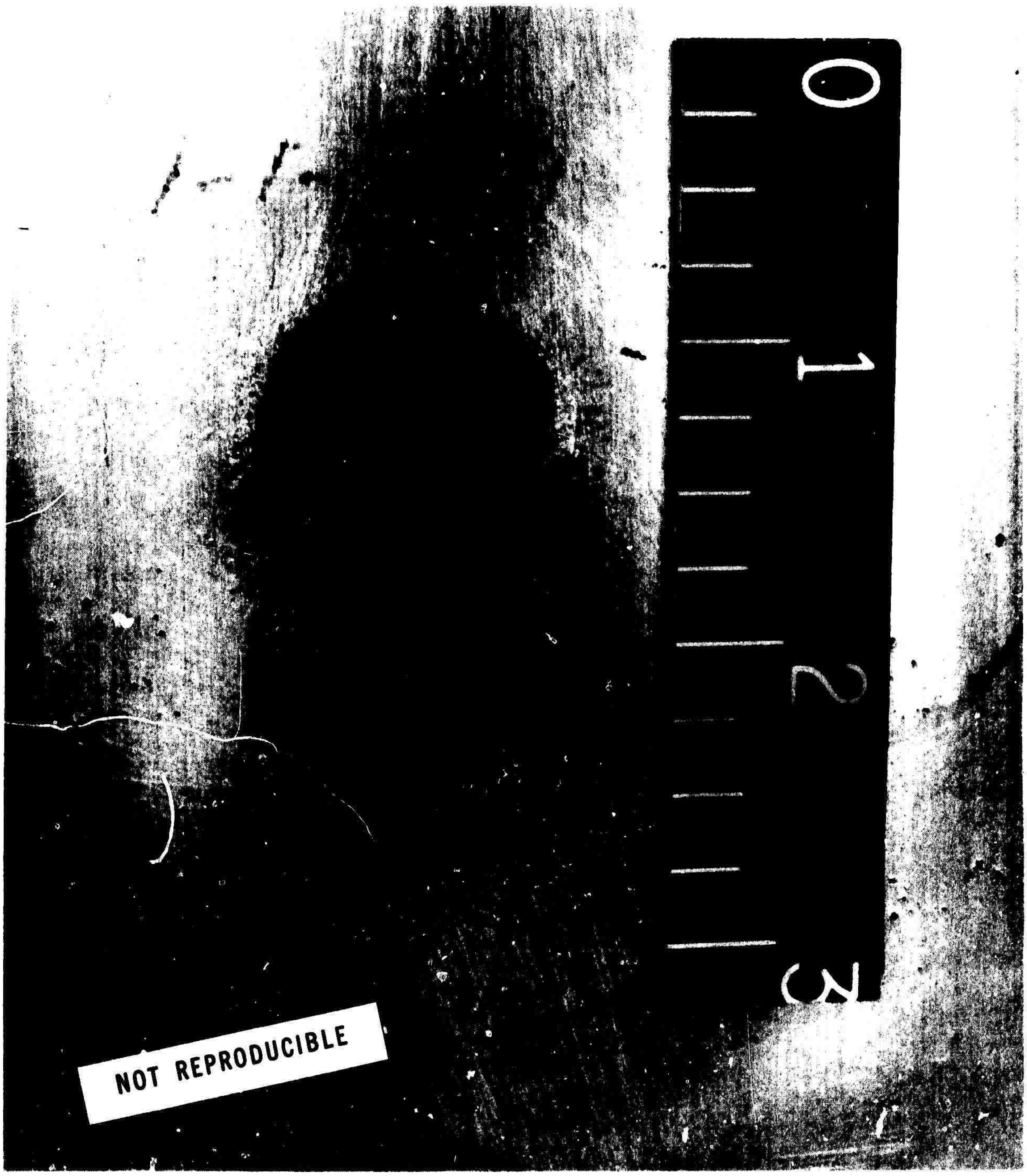

Figure 11. Nylon projectile, aluminum/steel target (Round 1-1-759)
Front face damage (impact velocity = 19,973 ft/sec)

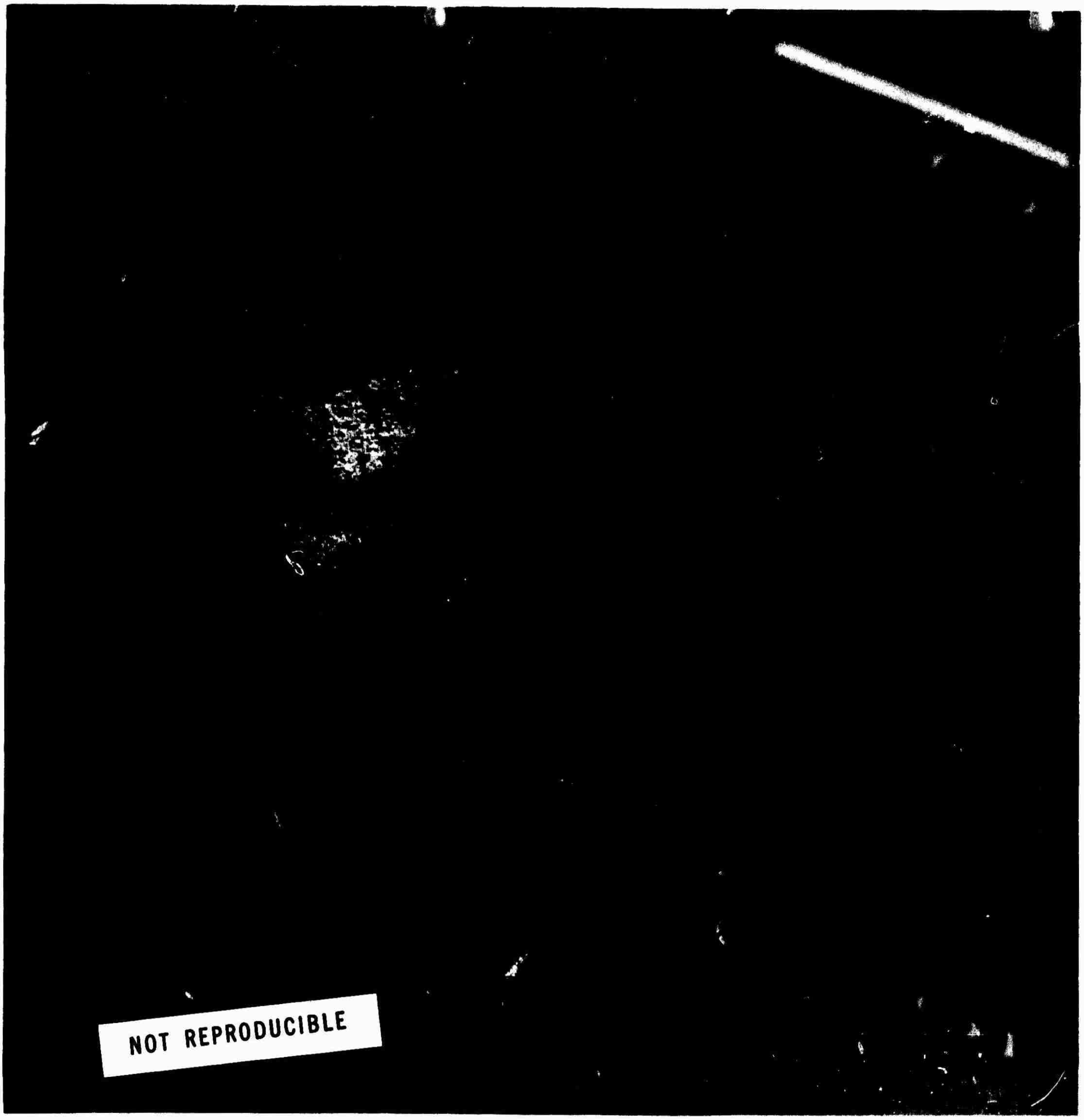

Figure 12. Nylon projectile, aluminum/steel target (Round 1-1-759)
Rear face damage (impact velocity = 19,973 ft/sec)

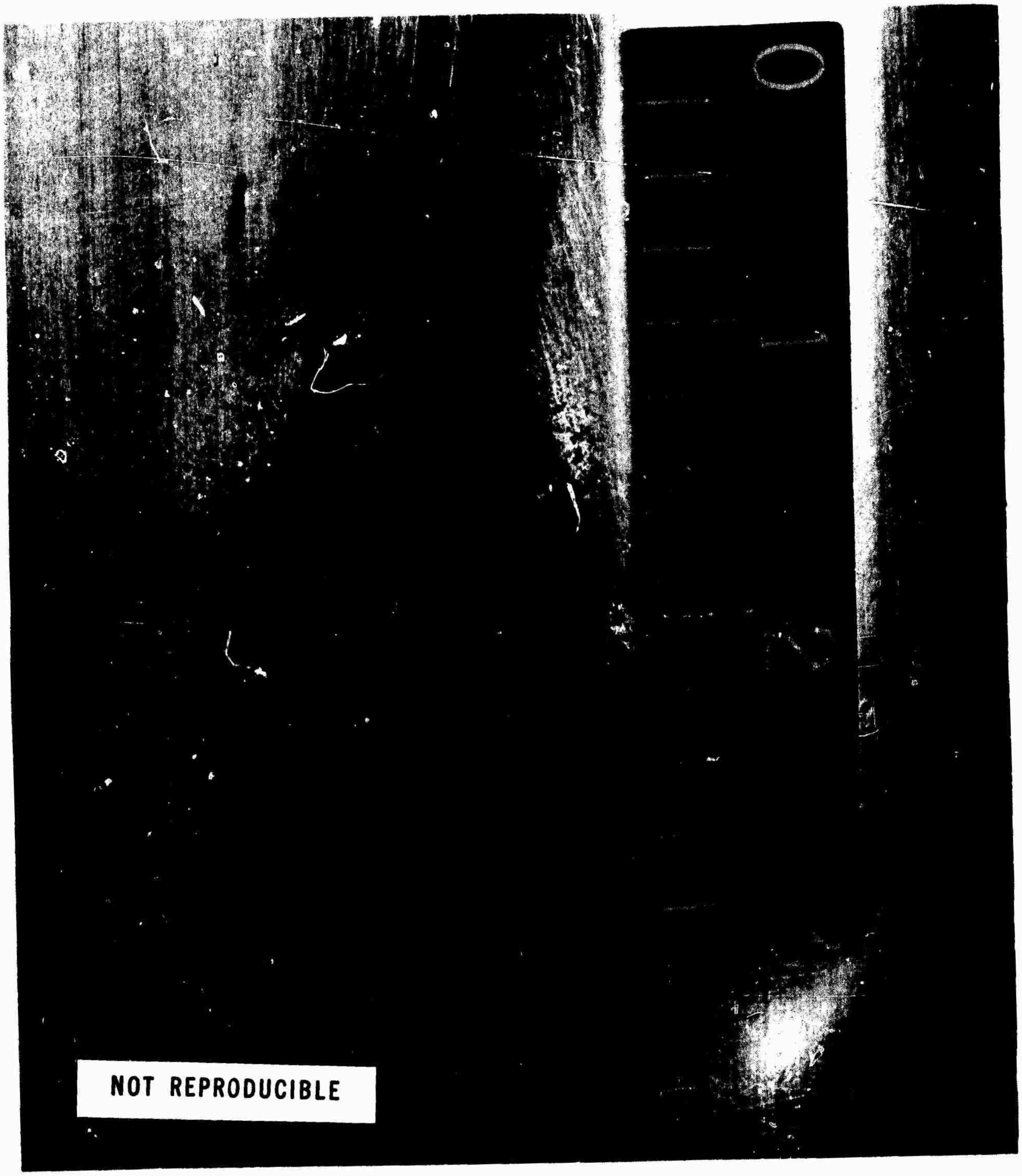

Figure 13. Nylon projectile, aluminum/steel target (Round 1-1-761)
Front face damage (impact velocity = 19,616 ft/sec)

Figure 14. Nylon projectile, aluminum/steel target (Round 1-1-761)
Rear face damage (impact velocity = 19,616 ft/sec)

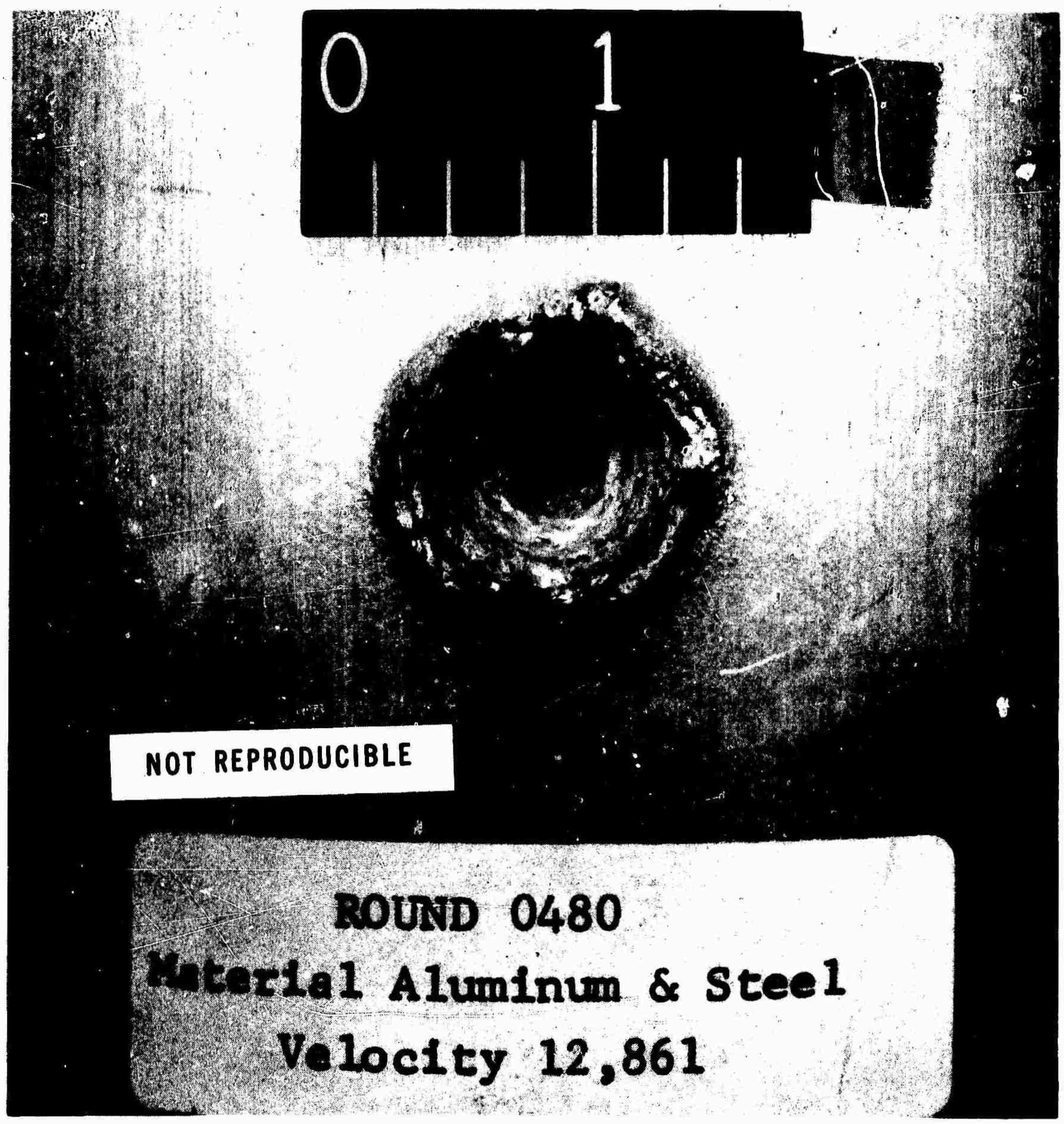

Figure 15. Aluminum projectile, aluminum/steel target (Round 0480)
Front face damage (impact velocity = 12,861 ft/sec)

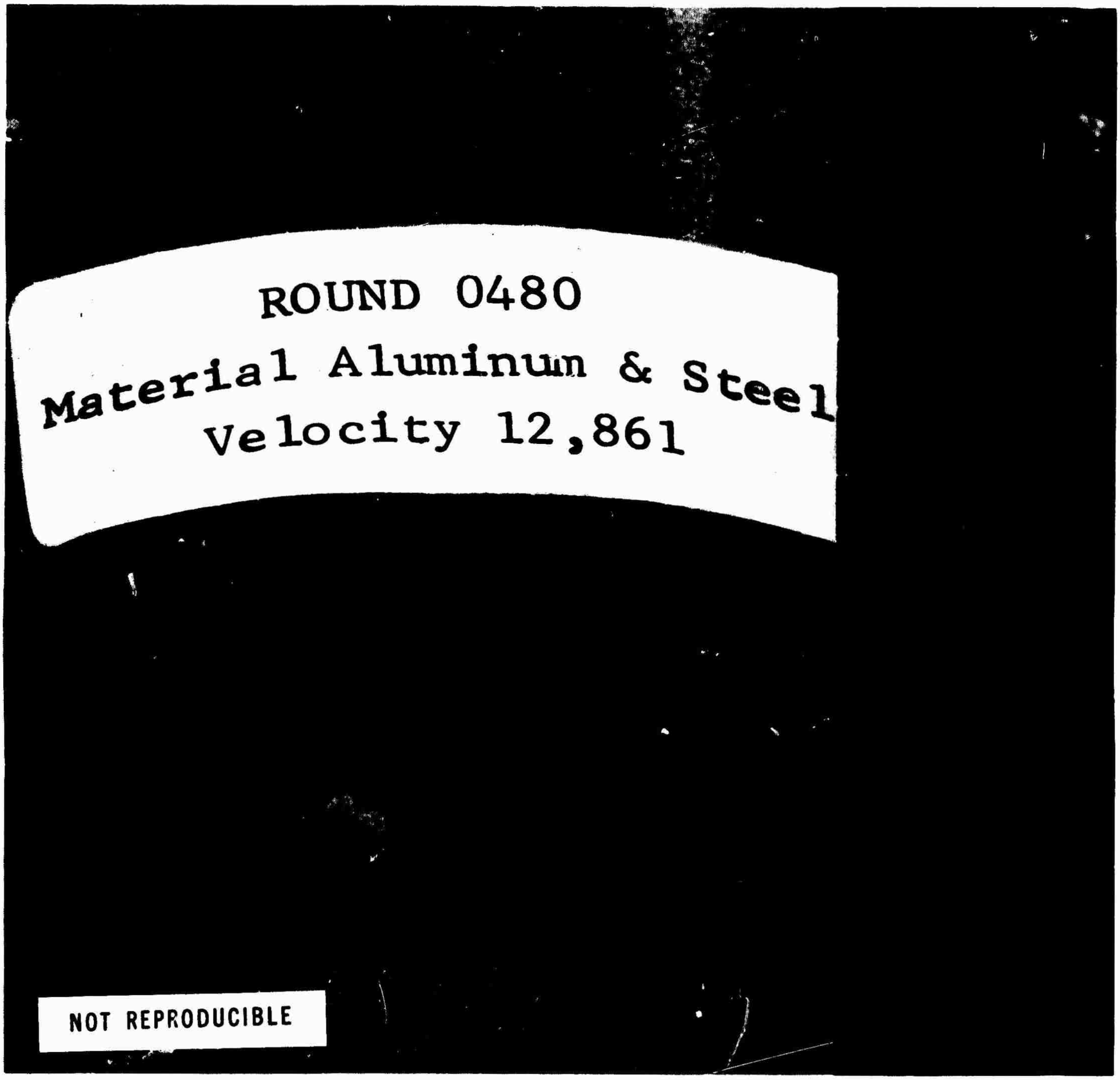

Figure 16. Aluminum projectile, aluminum/steel target (Round 0480)
Rear face damage (impact velocity = 12,861 ft/sec)

Figure 17. Aluminum projectile, aluminum/steel target (Round 0482)
Front face damage (impact velocity = 13 707 ft/sec)

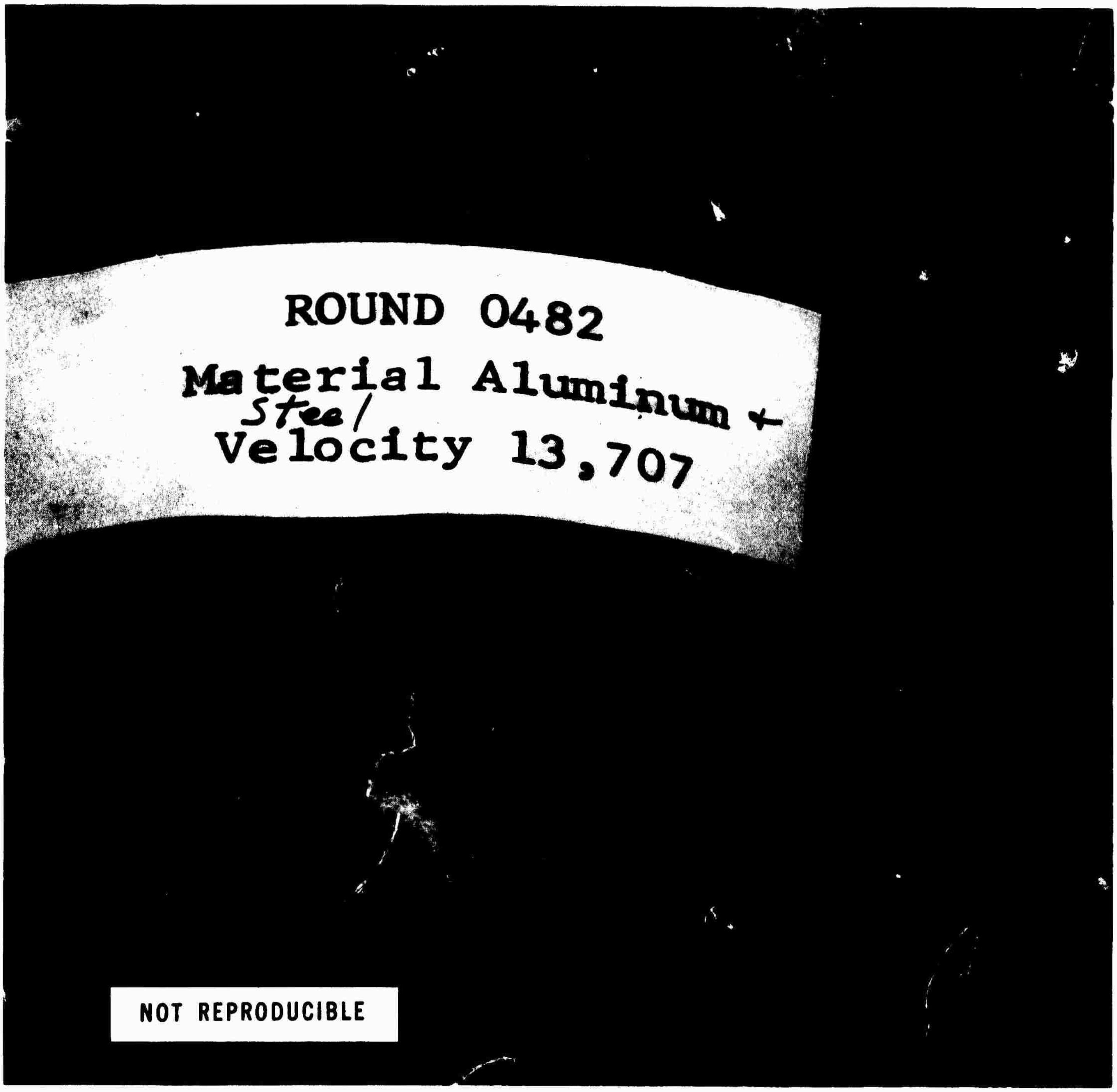

Figure 18. Aluminum projectile, aluminum/steel target (Round 0482)
Rear face damage (impact velocity = 13,707 ft/sec)

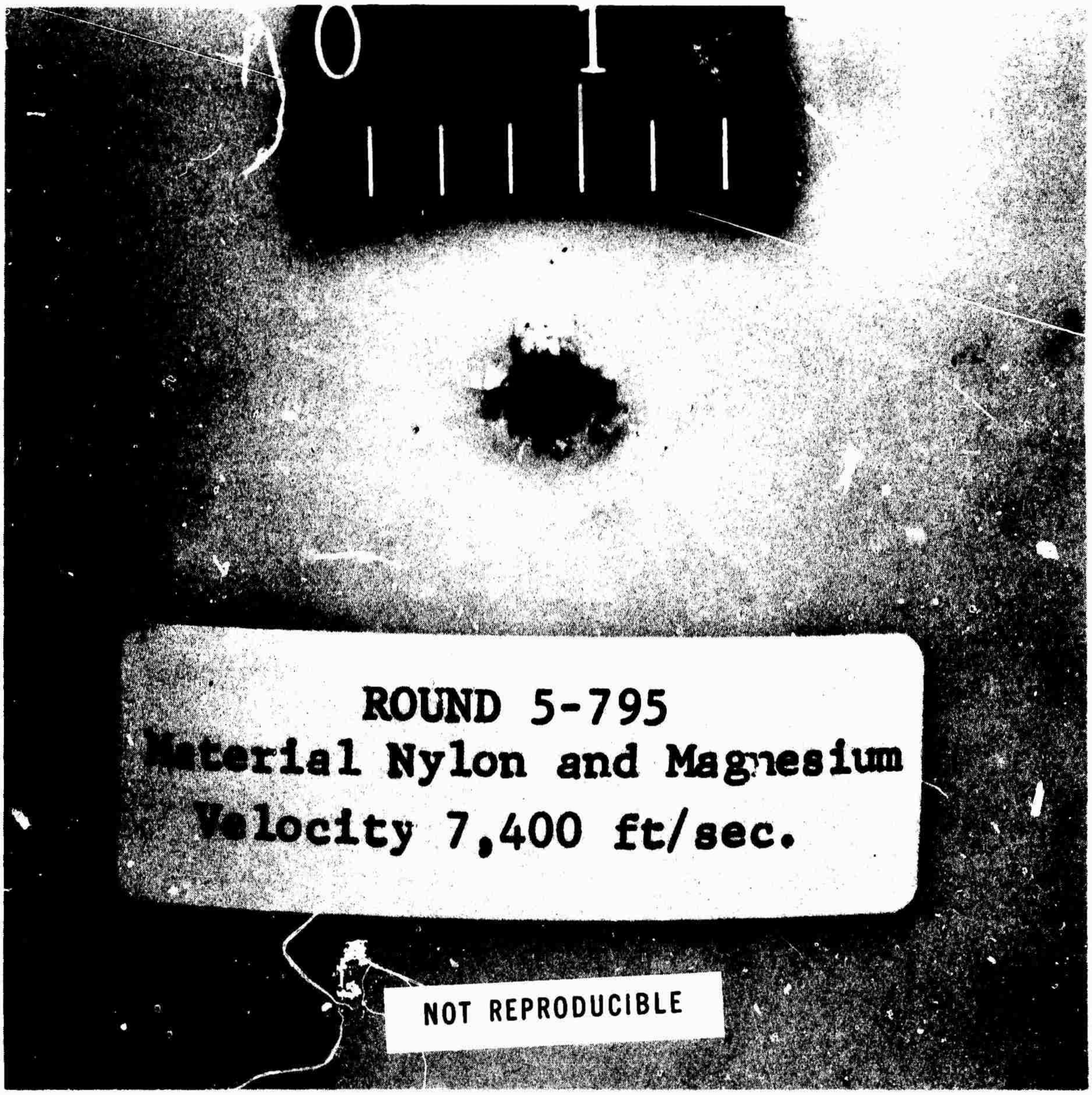

Figure 19. Polyethylene projectile, nylon/magnesium target (Round 5-795)
Front face damage (impact velocity = 7,400 ft/sec)

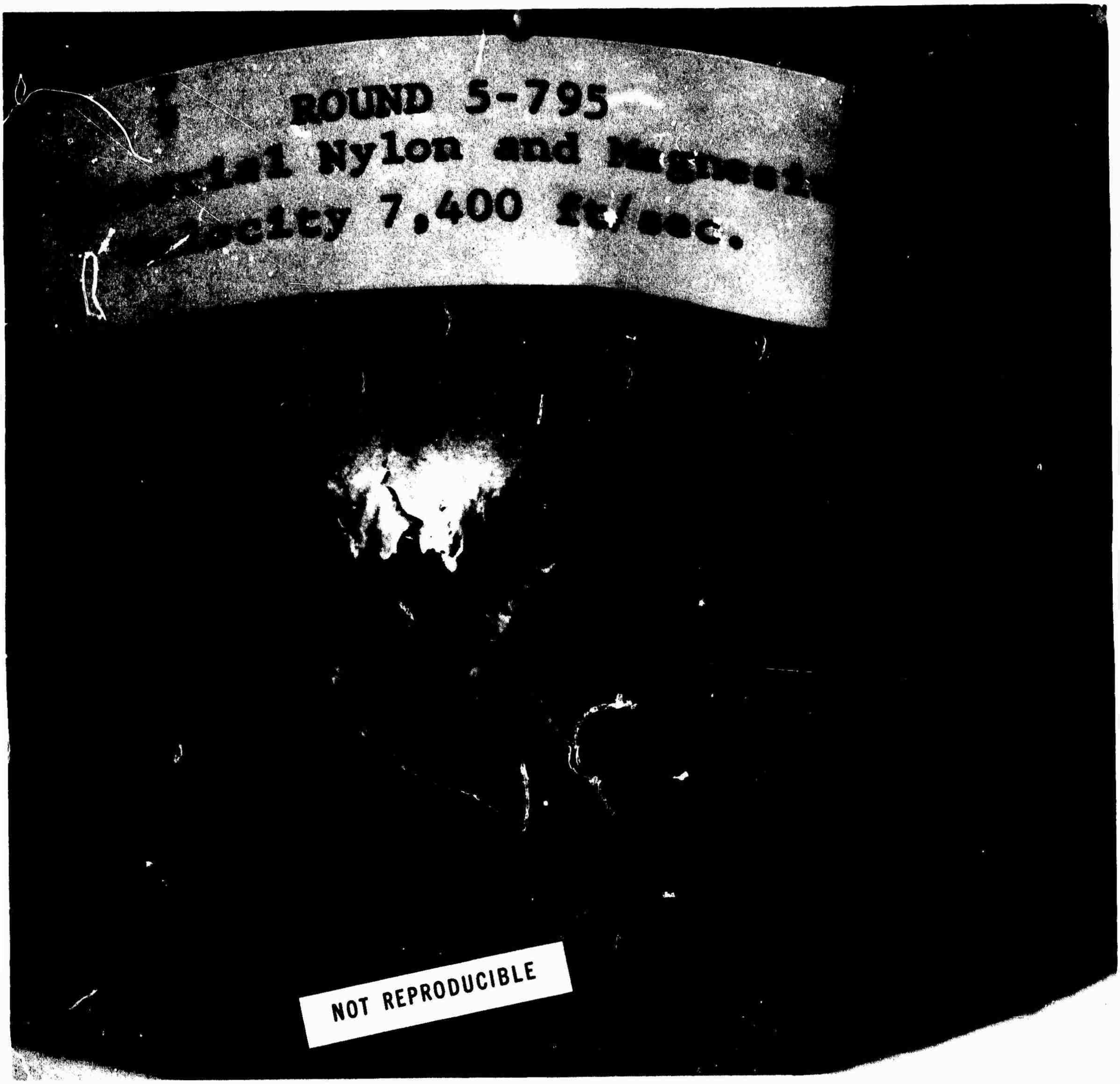

Figure 20. Polyethylene projectile, nylon/magnesium target (Round 5-795) Rear face damage (impact velocity = 7,400 ft/sec)

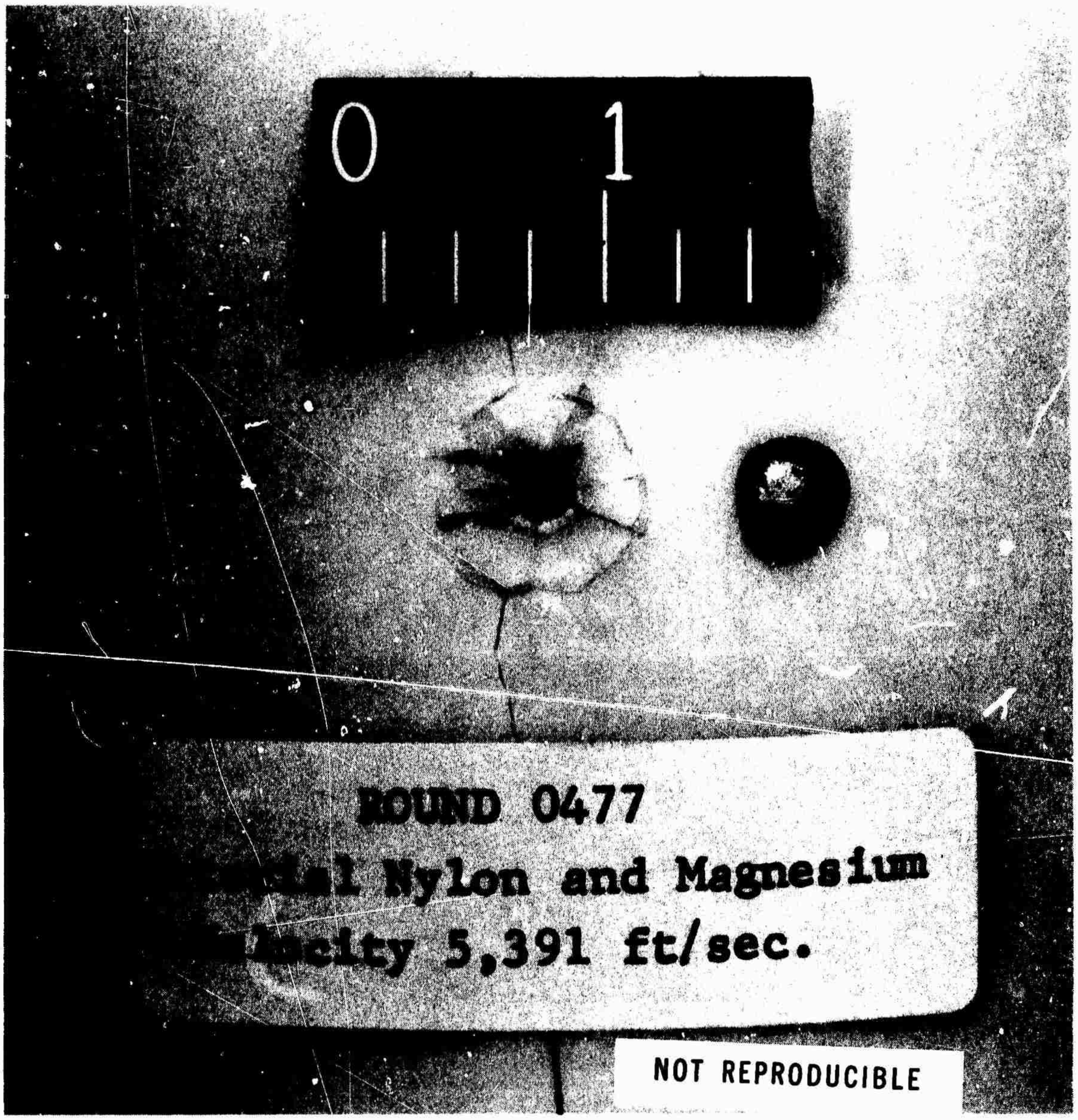

Figure 21. Aluminum projectile, nylon/magnesium target (Round 0477)
Front face damage (impact velocity = 5,391 ft/sec)

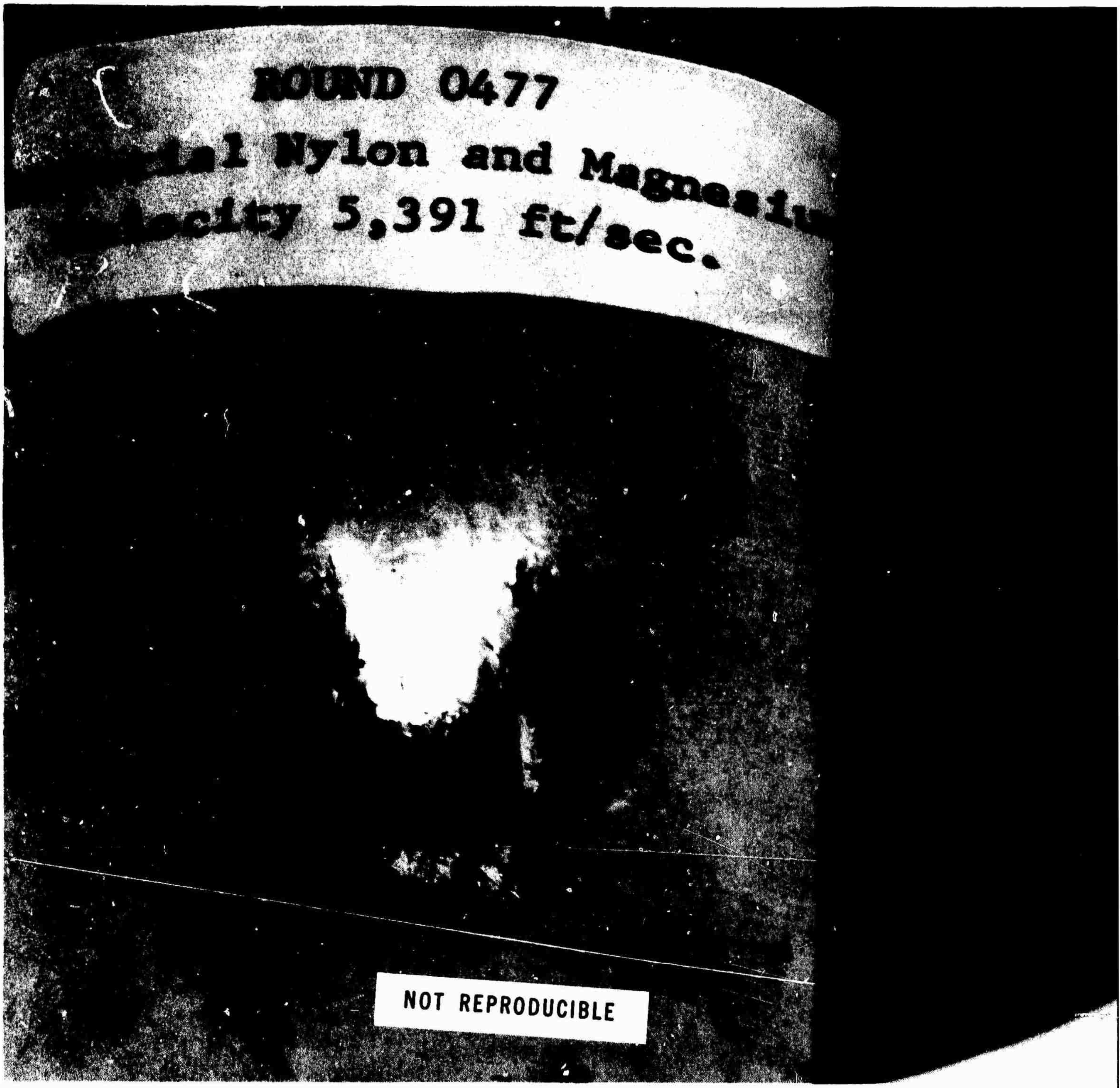

Figure 22. Aluminum projectile, nylon/magnesium target (Round 0477)
Rear face damage (impact velocity = 5,391 ft/sec)

APPENDIX: CHOICE OF MATERIALS USED IN THE TESTING PROGRAM

As mentioned earlier in this report, it is generally only convenient to obtain similitude of a partial type. It is usually most relevant to refer this partial similitude to the target. For such a situation,

$$\left(E_{m_t}/E_p\right)_1 = \left(E_{m_t}/E_p\right)_2$$

$$(p_i/\sigma_t)_1 = (p_i/\sigma_t)_2$$

The energy required to melt a pellet volume of the target is obviously determined by the weight of the pellet and the total heat required to cause a unit weight to change phase, from some arbitrary temperature. The energy required to cause pellet break-up by fracture may be characterized by the product of the pellet volume and the strain energy per unit volume for, say, tensile fracture. The energy in the pellet is, of course, simply kinetic energy $1/2\rho V^2$. The pressure at impact can be calculated from the normal shock relationships, provided the Hugoniot equations are known for the pellet and the target.

In order to choose suitable materials, the foregoing parameters were evaluated for a number of target/pellet combinations. The results for targets of aluminum and nylon impacted by various pellets are shown in Figures A1 and A2. From these results, it was concluded that, for an aluminum target, similitude could be achieved using, for instance, targets of lithium hydroxide, nylon, aluminum, etc. The latter two were chosen because of their availability and their dissimilar nature (plastic, metal). Similarly, a nylon target impacted by beryllium, lithium hydroxide, polystyrene, polyethylene, aluminum, etc., would produce similitude.

Acoustic Impedance Matching

In order to extend the concepts of similarity to specimens consisting of two distinct materials, tests were defined that

utilized the basic pellet/target combinations referred to above, with the difference that the target was constructed with an inner wall (0.1-inches thick) which differed from the outer shell (0.4-inches thick).

The choice of materials for the inner walls was based upon a need to maintain the ratio of acoustic impedances between the inner and outer walls equal in similar tests. To further enhance similarity, secondary requirements of approximately equal density and tensile strength-ratios were imposed.

While, as might be expected, it was difficult to attain all three requirements using readily available and conveniently fabricated materials, it was considered satisfactory to use inner walls of steel and magnesium for the specimens having an outer wall of aluminum and nylon, respectively. The following parameters resulted:

U.T.S. Ratio: $\dfrac{\text{Aluminum}}{\text{Steel}} = 0.364$

$$\frac{\text{Nylon}}{\text{Magnesium}} = 0.385$$

Density Ratio: $\dfrac{\text{Aluminum}}{\text{Steel}} = 0.344$

$$\frac{\text{Nylon}}{\text{Magnesium}} = 0.660$$

Acoustic Impedance Ratio: $\dfrac{\text{Aluminum}}{\text{Steel}} = 0.342$

$$\frac{\text{Nylon}}{\text{Magnesium}} = 0.220$$

The above-noted ratios were considered acceptable within the constraints of employing readily available materials.

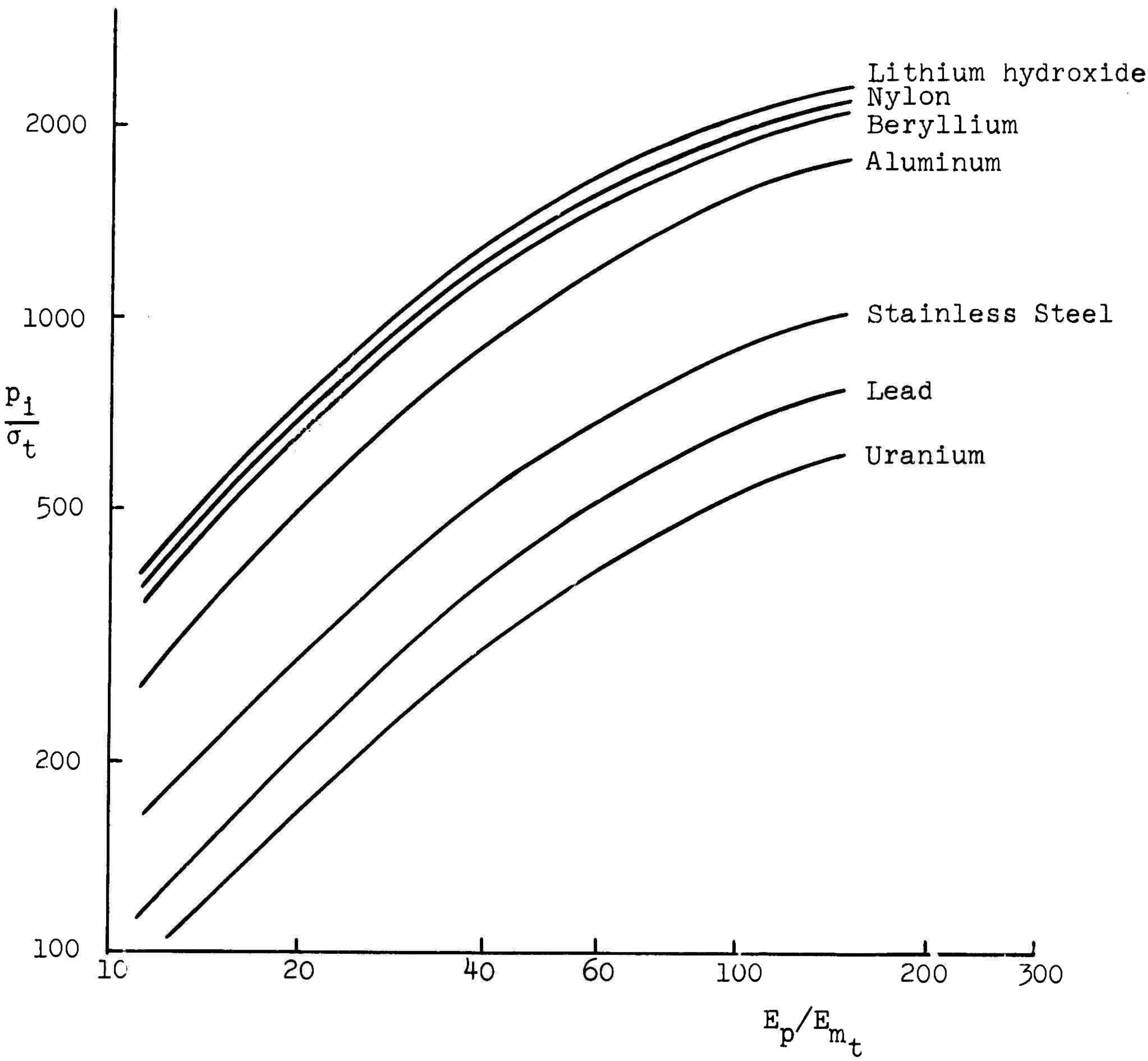

Figure A1. Typical similitude curves, nylon target

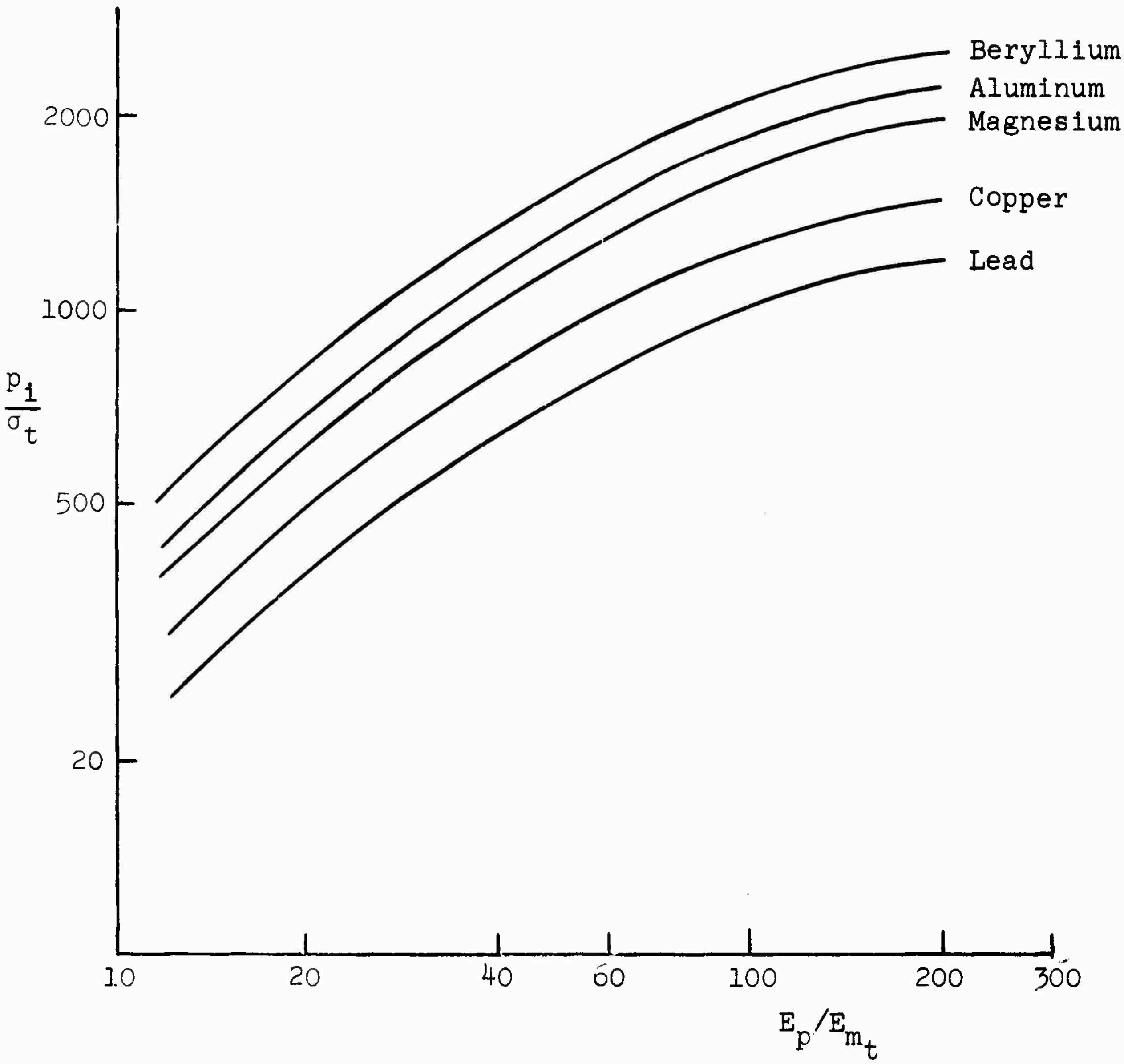

Figure A2. Typical similitude curves, aluminum target